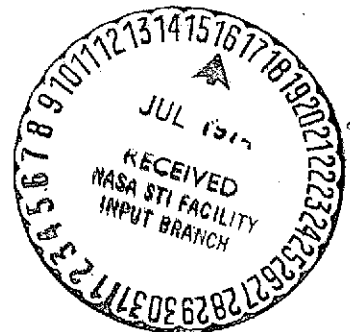# NASA TECHNICAL
MEMORANDUM

NASA TM X-64856

REPORT OF THE PLASMA PHYSICS AND ENVIRONMENTAL
PERTURBATION LABORATORY (PPEPL)
WORKING GROUPS

Volume I — Plasma Probes, Wakes, and
Sheaths Working Group
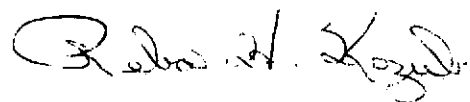
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George C. Marshall Space Flight Center

Marshall Space Flight Center, Alabama

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16. ABSTRACT

     It is shown in this report that a comprehensive in-situ study of all aspects of the entire zone of disturbance caused by a body in a flowing plasma would result in a large number of requirements on the Shuttle-PPEPL facility. However, a large amount of necessary in-situ observation can be obtained by adopting appropriate modes of performing the experiments. Requirements are indicated for worthwhile studies, of some aspects of the problems, which can be carried out effectively while imposing relatively few constraints on the early missions. Considerations for the desired growth and improvement of the PPEPL to facilitate more complete studies in later missions are also discussed. Problems needing further study are the dynamic characteristics of the booms while undergoing wake and sheath experiments, the elimination or reduction of $\vec{V} \times \vec{B}$ effects of the booms and boom-mounted instruments, the feasibility of using the Atmospheric Explorer as a subsatellite, and an improvement of present techniques and devices used in plasma diagnostics.

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PREFACE

In December 1971, OSS/MSFC initiated a study to determine the feasibility of carrying out active (perturbation) experimental studies of the ionospheric/magnetospheric plasmas, as well as laboratory plasma studies, from a manned orbiting laboratory facility housed in a Spacelab module and carried into orbit by the Space Shuttle. This proposed facility has subsequently become known as the Plasma Physics and Environmental Perturbation Laboratory (PPEPL). The scientific community responded to this idea in a number of different areas, and it became apparent that the general study, being carried out by TRW Systems, Inc. and an associated science advisory board, could not address all of the aspects of each individual area. Thus, working groups were organized in the three general areas of plasma probes, wakes, and sheaths; wave experiments; and magnetospheric studies. The specific purpose of the Plasma Probes, Wakes, and Sheaths Working Group was to investigate the feasibility of Shuttle-borne studies of the spacecraft-space plasma interaction, or, more generally, the characteristics of the flow of rarefied plasma over various types of bodies. Related experiments involving the utilization of diagnostic instruments and techniques, both for wake and sheath studies and for ambient plasma measurements, were also to be considered.

In addition to the inputs of individual working group members, two major sources of information were considered in arriving at the conclusions and recommendations presented herein. The findings of the TRW study (particularly the sections on wake and sheath studies and on propulsion and devices) provided much background information. It was also felt that additional input from the scientific community was desirable, and, to this end, the working group organized a special session on wakes and sheaths at the 1973 Spring meeting of the American Geophysical Union.

The reports from each of the three working groups are printed in separate volumes. This volume is an edited version of the report written by the Plasma Probes, Wakes, and Sheaths Working Group. Volumes II and III are the reports prepared by the Wave Experiments Working Group and the Magnetospheric Experiments Working Group, respectively.

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DEFINITION OF SYMBOLS

Symbol	Definition
N_+	ion number density
N_e	electron number density
N_0	neutral particle number density
V_s	velocity of spacecraft
k	Boltzman constant
T_e	electron temperature
m_+	mass of ion
m_e	mass of electron
λ_D	Debye length
R_0	wake generating body radius
λ_+	ion mean free path
λ_-	electron mean free path
$R_L(+)$	ion Larmor radius
$R_L(-)$	electron Larmor radius
e	unit of charge
ϕ_s	spacecraft potential relative to the ambient plasma
$\vec{B}$	magnetic induction vector
I_e	electron current

VOLUME I – PLASMA PROBES, WAKES, AND SHEATHS WORKING GROUP

I. INTRODUCTION

It is well known that the bulk of matter in the universe exists primarily in the plasma state, ranging from the dense, collision-dominated stellar material to the very tenuous, collisionless plasmas of the ionosphere, magnetosphere, solar wind, and the interstellar gas. Since all bodies move in space, one of the most common occurrences in nature, and therefore one of prime scientific interest, is the characteristic way in which plasma flows around various types of bodies. The governing physical mechanisms of such interactions are not well understood and present a basic problem in plasma physics which is fundamental to understanding the many natural processes, including some aspects of the celestial environment of the earth. To this end, the investigation of the interaction between orbiting spacecraft or test bodies and the ionospheric plasma offers a unique opportunity to study the characteristics of the flow of a natural, unbounded plasma around a variety of bodies.

Much of the background information for this study was obtained from References 1 through 3.

A. Some Characteristics of the Disturbed Zone

The wake of a satellite is known to be void of ions and significantly depleted of electrons in the near wake region and to approach ambient conditions some distance downstream. Some theories, laboratory studies, and a limited amount of in-situ data also indicate ion/electron enhancements in the midwake region [4-7], while in the far wake it has been anticipated that trailing shock type disturbances, which propagate away from the wake axis, may be observed [8,9].

The more subtle aspects of the disturbed zone may include localized variations in electron temperature, which have been observed in the near wake [10] but could, in principle, occur throughout the wake region. Also, temporal oscillations have been indicated by some in-situ measurements [11], and one would expect a variation in the magnitude and direction of ion flux in the wake region for ions of different masses.

Finally, it is anticipated that the above characteristics of the disturbed zone will be governed by a number of parameters which depend on both the nature of the body and the inherent plasma characteristics. At present, it is difficult to assess the effects of all the possible plasma flow parameters. However, one would expect those given in Table 1 to have a significant bearing on the characteristics of the disturbed zone. (The expected ranges for these parameters over typical orbits accessible to the Space Shuttle are given in column 3). This is not an exhaustive list of all possible plasma and environmental parameters, and there may be additional influences to be considered.

B. Present Status

The picture obtained of the disturbed zone from the presently available in-situ data (most of which come from the Explorer VIII, Ariel I, and Explorer XXXI satellites) is one primarily of electron behavior. Very little information is available on the distribution of ions around orbiting spacecraft. Including the observations taken behind a spherical ion trap probe on Ariel I, reliable data have been obtained only at distances of $1R_0$, $2R_0$, and $5R_0$ from the center of the wake-generating body (where R_0 is the body radius). In addition, a single axial profile and one transverse profile of ion and electron fluxes taken behind the Gemini 10 spacecraft and the Agena Booster, respectively, are available.

All of the above data were obtained for relatively complex bodies (in terms of geometry and/or surface materials and potential distributions) and involve a number of different types of probes on different satellites in various orbits. A more complete and systematic mapping of the disturbed zone is needed to establish the governing physical mechanisms of the spacecraft-space plasma interaction and for a thorough comparison with theoretical and laboratory studies.

Details of the above in-situ data and the results obtained are given in Appendix A.

Several theoretical treatments of the wake and sheath problem exist. They differ primarily in the method of numerical analysis and the simplifying assumptions utilized to obtain a solution (see Appendix B). They also exhibit corresponding differences in the predicted characteristics of the disturbed zone; i.e., the treatment by Al'Pert [12] assumes no perturbation of the ion motion by electric fields associated with the body and predicts essentially no structure within the wake region, while that of Taylor [7] considers the electric field

TABLE 1. SOME USEFUL PARAMETERS FOR WAKE AND SHEATH STUDIES[a]

Parameter Description	Symbol	Values for Altitude Range of 400 to 1200 km[b]
Ratio of Ion/Electron and Neutral Particle Densities	$\dfrac{N_+}{N_0}$	$5 \times 10^{-3} \rightarrow 10^{-1}$
Ion Speed Ratio (Mach No.)	$\dfrac{V_s}{\left(2kT_e/m_+\right)^{1/2}}$	$\sim 6 \rightarrow \approx 3$
Ratio of Electron Thermal Speed to Test Body Orbital Velocity	$\dfrac{\left(\dfrac{2kT_e}{m_e}\right)^{1/2}}{V_s}$	$\sim 37 \rightarrow \sim 41$
Debye Number	λ_D/R_0	$4 \times 10^{-3} \rightarrow 4 \times 10^{-2}$
Ratio of Ion/Electron Mean-Free-Path to Test Body Radius	$\lambda_\pm/R_0$	$10^3 \rightarrow 10^5$
Ratio of Ion/Electron Larmor Radius to Test Body Radius	$R_L(+)/R_0$ $R_L(e)/R_0$	$\sim 5 \rightarrow \sim 8$ $\sim 4 \times 10^{-2} \rightarrow \sim 6 \times 10^{-2}$
Ratio of Ion and Electron Number Densities	N_+/N_e	~ 1 (ambient)
Dimensionless Test Body Potential	$\dfrac{e\phi_s}{kT_e}$	~ -5

a. Other factors which may affect experimental results include photo and secondary electron emissions, surface material and outgassing of the body, the local electric field vector, the various reasonant frequencies of the plasma, etc.

b. Values given are for a test body of 1 m radius.

forces on the streaming ions and predicts an ion flux enhancement (or peak) structure in the midwake region. At present, the physical assumptions required to obtain solutions in theoretical treatments cannot always be justified. A systematic in-situ study is required to establish the critical parametric relations and, thus, the allowable assumptions, as well as to provide a means of corroborating the theoretical results.

Ground-based laboratory studies have also indicated ion flux enhancement in the wake region, as well as the effects of certain parameters on the wake characteristics (see Appendix B). However, all aspects of the ionospheric environment cannot be properly simulated in the laboratory, i.e., the geomagnetic field and the correct velocity distribution for ions. In-situ measurements are required to ascertain the composite effects when all aspects of the environment act together and to corroborate the conclusions obtained from the more restricted laboratory investigations.

C. Approach

It is apparent that (1) both theoretical and laboratory studies have inherent limitations, and, therefore, comparisons with in-situ measurements are required to obtain an accurate and reliable description of the wake and sheath phenomena, and (2) the available in-situ data are incomplete and are presently not capable of providing the grounds for extensive and systematic comparisons with theoretical and laboratory studies.

Evidently, a new experimental approach is required which will provide for a detailed mapping of all governing flow parameters within the disturbed zones around a variety of different types of bodies as well as simultaneous measurements in the ambient, undisturbed medium. Such an approach excludes single body satellite or sounding rocket experiments.

It is the consensus of this working group that, although some aspects of the spacecraft-space plasma interaction can be studied only with the aid of subsatellites, a large amount of the required in-situ observations can be obtained from the Plasma Physics and Environmental Perturbation Laboratory (PPEPL)-Space Shuttle facility with the use of two maneuverable 50-meter booms. The booms will: (1) remove the experiment from the immediate Shuttle environment and (2) allow independent manipulation of the wake-generating body and a package of diagnostic instruments to obtain a mapping of the wake and sheath characteristics.

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II. SCIENTIFIC OBJECTIVES

The primary scientific objective is a detailed study of the characteristics and governing mechanisms of the flow of rarefied plasma around various types of bodies. Such studies should include measurements of the ac and dc characteristics of the wake and sheath, including the behavior of the plasma medium and electric and magnetic fields. As a result of the increased payload capability of the Shuttle, it is now feasible to study the wake and sheath characteristics of very large bodies and bodies with associated magnetic fields. Some examples of these studies and some possible applications, which are both of a technical and astrophysical nature, are briefly discussed below:

1. Applications of Wake and Sheath Characteristics to Measurements of the Ambient Medium — The plasma wakes of sounding rockets and satellites have been used to determine the magnitude and direction of bulk drifts in the space plasma through which the vehicle moved. A more in-depth knowledge of the wake and sheath phenomena may reveal additional diagnostic capabilities; for example, it may be possible to determine the mean plasma composition from the amount of electron depletion in the near wake. In view of the possibilities of Venus and Mars orbiters carrying probe experiments, diagnostic applications of the vehicle wake and sheath could be utilized on such planetary missions for essentially no additional cost in weight or power.

2. Controlled Study of the Probe-Medium Interaction — The interaction between a diagnostic system and the medium that is being measured is a problem which is basic to all experimental studies. Although present diagnostic devices are sufficient to make the initial studies of the disturbed zone around a spacecraft, the direct measurement probes such as Langmuir-type electrostatic probes and Retarding Potential Analyzers (RPAs) are subject to self-wakes, as well as the wake of the spacecraft to which they are attached. Since the standard analysis of data from these types of probes assumes a Maxwellian velocity distribution in the ambient medium, wake and sheath effects may affect the interpretation of both the temprature and density of charged particles. Investigation of the ionospheric plasma flow over bodies which model various aspects of these types of probes should lead to the development of more comprehensive probe theories that account for such wake and sheath effects. Such improvements in diagnostic techniques would apply directly to in-situ investigations of the near-earth plasma environment, i.e., the ionosphere and magnetosphere.

3. Interaction of Planetary Moons with Planetary Ionospheres — As a particular example of a planetary moon-ionosphere interaction, Io (one of the moons of Jupiter) is known to orbit within regions containing radiation belts

very similar to the Van Allen belts associated with earth. There are also indications that Jupiter has an ionosphere and magnetosphere which extend beyond the orbit of Io. It is, therefore, quite plausible that the interaction of such a moon with its planetary ionosphere would exhibit certain resemblences to the interaction between an artificial satellite and the earth's ionosphere. In fact, it has been suggested that the well-known burst of decametric radiation emissions from Jupiter are caused by the interaction of Io with its plasma environment in much the same way that the artificial satellite ATS-5 was observed to interact with the earth's magnetospheric plasma [13].

4. Solar Wind Interaction with Certain Celestial Bodies — The flow of ionospheric plasma over orbiting bodies can serve as a model for some aspects of the solar wind's interaction with bodies having negligible intrinsic magnetic fields and atmospheres, e.g., the earth's moon, some of the planets such as Mercury, and possibly some of the asteroids. Modeling of the solar wind interaction with comets, the earth, and other bodies with associated magnetic fields and/or atmospheres presents a more difficult scaling problem and would require more complex wake-generating bodies. However, it may be possible to investigate certain mechanisms involved in the flow of the solar wind around these bodies; for example, the use of a magnetized wake-generating body to study particle-field interactions.

III. EXPERIMENT REQUIREMENTS

A major advantage of Shuttle-borne studies is the capability for active control of experiments and onboard, real-time reduction and display of key constituents of the data. This capability will be especially useful in wake and sheath studies where on-the-spot decisions must be made concerning the weighting of data and modification of the experiment in such a way as to allow observation of interesting areas and effects as they occur. For example, it may be necessary to reprogram the mapping maneuvers to obtain data at key locations in the wake region. The capability of real-time data display and control of the experiment should also considerably reduce the time and effort required in data reduction by allowing careful acquisition of the data. It will also allow selection of the most interesting portions of the data for transmission to the ground in its raw and/or reduced form where it could then be further analyzed by the principal investigator (PI). In this way, experiments could be evaluated and modified throughout the 7-day sortie missions.

Based on the guidelines presented in the study by TRW Systems, Inc. [3], it was assumed that in early flights the PPEPL will consist of only the most essential systems and instrumentation and that later flights will include improvements and growth of the facility. Therefore, the initial flights and the capabilities they can provide for wake and sheath type studies will be discussed first. Although a number of different aspects of the disturbed zone can be investigated on these early flights, there are certain limitations. Specifically, it is not feasible to carry out an investigation of the wake and sheath characteristics of the Space Shuttle on such a mission, nor is it likely that measurements can be obtained for distances greater than 75 to 80 body radii downstream, even for relatively small test bodies. Therefore, the discussion will also include some improvements and growth possibilities that would provide the capability for more complete wake and sheath studies on later missions.

A. Requirements Related to PPEPL Design

1. EARLY MISSIONS

Even though it is technically a single body in the early flights (when it is unlikely that a subsatellite will be available), the Shuttle-PPEPL will eliminate the problems inherent in rocket and satellite-borne experiments. To illustrate these problems, one notes that the measurements were limited to fixed distances very near the body; they did not, in any given experiment, provide reliable data on all major variables involved; and they were not made simultaneously with complete measurements of the total ambient medium. In these respects, the Shuttle-PPEPL will provide the capabilities of a multibody system. This can be accomplished by utilizing a pair of moderately long (50-meter) maneuverable booms located on the instrument pallet of the PPEPL. By mounting a wake-generating body on one boom and a complement of diagnostic instruments on the other, the booms can be maneuvered to accomplish a mapping of the plasma flow field surrounding the body. In principle, the coordinate system for mapping the wake could be made as fine as desired. However, there will be practical limitations set by the characteristics of the boom (e.g., oscillations and position sensing and control) and the amount of time available for conducting the experiment. These limitations will be discussed in more detail in the following paragraphs.

The capabilities of the facility would be greatly enhanced by a second complement of diagnostic instruments (not necessarily identical to those used to map the wake and sheath zones) to independently measure the ambient

plasma conditions. This would allow separation of temporal and spatial iono-
spheric fluctuations from the wake perturbations. If included in the CORE
instrumentation of the PPEPL facility, such an instrument package would be
useful for a large number of the plasma perturbation studies presented in
Reference 1 in addition to experiments of the wake and sheath types.

Although it is doubtful that the experimental approach described above
lends itself to direct measurements of the plasma disturbance caused by the
Space Shuttle, a fairly complete and comprehensive study can be made of the
wake zones and the frontal sheath region of smaller test bodies. It appears
that if reasonably complete complements of diagnostic instruments are available
(both for mapping and ambient measurements) then, in principle, it should be
possible to obtain information on all aspects (both of a spatial and temporal
nature) of these regions. On any given mission, it would probably be possible
to study only one or two bodies and one or two sets of plasma parameters
(e.g., at perigee and apogee). A complete investiation of the characteristics
of the wake and sheath zones will require a number of different bodies and
orbits. However, given a number of missions, such an approach should
accommodate a majority of the experiment concepts presented in the wake and
sheath section of Reference 1.

a. Requirements

(1) Orbital. The wake and sheath type experiments must be carried
out in regions where the ionospheric plasma is well behaved, i.e., smoothly and
slowly varying in a predictable manner. Since almost all orbits provide these
conditions to some extent, wake and sheath experiments can be carried out (to
varying degrees of completeness) without placing strict orbital requirements
on the Shuttle. However, the optimum conditions for these experiments would
be provided by an elliptical orbit with a low angle of inclination in order to
maximize both the time available for conducting the experiments and the range
of plasma parameters available between perigee and apogee.

(2) Boom Articulation. The region of the disturbed zone which is
accessible with a boom-mounted experiment is limited primarily by the ratio
of the radius of the wake-generating body to the length of the boom. For 50-
meter booms, a body radius of 5 meters would limit the downstream wake
measurements to something on the order of 15 radii. The use of larger bodies
would, therefore, produce very limited results in the far-wake region. Con-
versely, the minimum size of the test body is limited (probably to something
on the order of a 1-meter radius) by the spatial resolution of the diagnostic
package, the perturbations caused by it, and the minimum coordinate grid size
attainable with the booms.

The data obtained from TRW and presented in Reference 2 indicate that the 50-meter booms can be swept at a rate of 0.5 deg/sec and extended at approximately 18 cm/sec when supporting a load of 25 kg (55 lb). This limited maneuvering rate, along with the time required for measurements by swept probes, implies that a limited number of data points will be obtained within the 10 to 15 min per orbit when the ionosphere is suitable for conducting these types of experiments. Some swept probes require as much as 4 sec for a complete cycle. For such cases, a maximum of 250 measurements could be made during the above time period if the probe operated continuously. However, if the probe were required to remain stationary at data points, much less data would be obtained. It will, therefore, be necessary to concentrate data more in regions expected to have interesting characteristics (e.g., possibly in a region ranging from the body surface out to the distance $S \cdot R_0$, where S is the ion velocity ratio and R_0 is the body radius). This implies a slow movement of the booms in the regions of interest and more rapid movement elsewhere. During such maneuvers the booms will suffer oscillations and end tilt proportional to the accelerations they undergo. Since the position and orientation of the instrument package in the wake (where rather steep gradients of the plasma characteristics may occur) is critical, this would have an adverse effect on the accuracy and reliability of experiments, particularly in the case of very small bodies, as mentioned above.

The acceleration on the booms can possibly be reduced by extending them in a plane containing the Spacelab axis and rotating the Shuttle about this axis while maintaining the orbital velocity vector perpendicular to the axis of rotation. Mapping maneuvers would then require an adjustment of the boom tip separation only once per revolution. The maximum allowable Shuttle rotation rate is about 1 rpm. This would allow 10 to 15 traverses of the wake during the portion of the orbit when the ionosphere is reasonably uniform.

(3) Mounting. The wake-generating body must be electrically insulated from the boom, capable of being biased, and much larger than its support structure. It may, therefore, be desirable to mount it on a small (approximately 5-meter) boom which is rigidly attached to the end of the 50-meter boom. If two small booms are mounted perpendicular to the 50-meter boom, in a T arrangement, the body could be mounted at one end and the CORE diagnostic package for ambient measurements at the other. A 10-meter separation of the probes from the body [which can be made very clean and should, therefore, be free of outgassing and electromagnetic interference (EMI)] should be sufficient at Shuttle altitudes. The diagnostic probe package (CORE and experimental) should also be mounted so that an orientation parallel (to within a few degrees) to the velocity vector can be maintained during mapping maneuvers.

(4) EVA. Although an EVA is not essential for the first stages of these types of experiments, it would greatly increase the utility of the PPEPL facility, providing the astronauts with much the same capability as a laboratory experimenter (i.e., the ability to modify the experimental setup, to repair or replace faulty instruments or apparatus, etc.). In the case of wake and sheath experiments, the wake-generating body, as well as the diagnostic instruments, could be changed to provide a wider range of experiments on a given mission. It would be worthwhile to weigh the advantages and also the implications of an EVA capability (such as expense and complexity of the PPEPL, use of astronaut time, etc.) against the requirement for a greater number of missions needed to achieve the desired results from the various areas of investigation given in Reference 1, if the PPEPL does not have such a capability.

2. LATER MISSIONS

a. Potential Applications of Subsatellites. As the PPEPL facility grows and matures into the baseline laboratory, it is anticipated that the early addition of subsatellites will be one of the major improvements. This would be a particularly fruitful addition in terms of wake and sheath experiments. A relatively simple subsatellite would allow:

1. Investigation of plasma and other environmental perturbations produced by the Shuttle.

2. Essentially unlimited capability to observe the far wake and, possibly, shock structures associated with both test bodies and the Shuttle.

3. Investigation of the wake and sheath characteristics of very large bodies.

To provide these capabilities, a subsatellite would need to meet the following basic requirements:

1. Provide some degree of maneuverability.

2. Provide an accurate indication of position with respect to the PPEPL and orientation with respect to the velocity vector.

3. Carry a complete complement of diagnostic instruments.

4. Transmit data to the PPEPL in real time.

5. Provide a clean, unipotential, and geometrically simple body.

The last requirement has a dual purpose. First, if the subsatellite is used as a vehicle to maneuver a complement of diagnostic probes through the disturbed zone of the Shuttle or some other body, it must be clean (free of outgassing and EMI) so that it will not interfere with the measurements. Secondly, if the subsatellite is to be used as a wake-generating body, the same requirements apply, with the addition that the body should also be geometrically simple with a unipotential surface. Optimally, the subsatellite would be a conducting sphere, since this is phenomenologically and mathematically the simplest three-dimensional body to analyze. Because of the mathematical simplification, most theories deal with spherical bodies, which in itself presents a sufficient reason for investigating the wakes of bodies with this geometry.

      b. The Atmospheric Explorer (AE) Satellite as a Subsatellite. Probably one of the most practical and most cost-effective ways to obtain a subsatellite for the Shuttle-PPEPL facility would be to use the existing AE Satellite which contains all of the essential systems to meet the requirements for wake and sheath studies listed above [14]. The experiment or instrument payload can weigh up to 95 kg (210 lb), occupy a volume of about 12 000 cm^3, and use an average of 4000 W-min electrical power per orbit. This AE Satellite also has maneuvering capabilities [159 kg (350 lb) fuel providing a total ΔV of 610 m/sec (2000 ft/sec)] which are adequate for changing its position in space and maintaining a fixed attitude to within 1 deg (determined to an accuracy of 0.5 deg). Although the AE Satellite carries adequate fuel for mapping of the wake and sheath regions and return to the PPEPL, in its present form its maneuverability is limited by the maximum available thrust of approximately 13.3 to 17.8 N (3 to 4 lb). Modification of the control thrusters to provide increased maneuverability would, therefore, be most useful and appears to be quite feasible.

      If possible, another modification that is desirable is the enclosure of the AE Satellite in a conducting, spherical outer shell in order to obtain a simplified wake-generating body, for the reasons discussed in the previous section. Although this would preclude the use of solar cells for power, three nickel-cadmium batteries, which provide a total of 18 W-hr, are included in the baseline design of the satellite and could provide power for short periods of time. (It is anticipated that wake and sheath experiments would normally be limited to something on the order of 10 to 15 min because of ionospheric conditions.) Other systems, such as the control thrusters and attitude sensors, will be required for satellite operation and, therefore, cannot be enclosed; however, it may be possible to use a partial shell.

B. Diagnostic Instrumentation

1. AMBIENT MEASUREMENTS

The success of the PPEPL and a large number of plasma experiments will depend on accurate and reliable measurements of the ambient environmental space plasma. Therefore, the Probes, Wakes, and Sheaths Working Group using their past experience with a variety of plasma diagnostic type experiments, compiled a list of variables considered essential to most PPEPL experiments and a partial list of the experimental methods presently considered most appropriate to the measurement of each of these parameters. It is suggested that these instruments become the basis of a CORE instrument package to provide the characteristics of the ambient plasma environment of the PPEPL for all experiments. In many active experiments, this package will also provide the needed monitoring of changes in the environment caused by the experiment.

Table 2 presents a list of variables, a corresponding listing of diagnostic probes and techniques, and the requirements and estimated weight of each instrument. This is not intended to represent a complete listing of variables or instruments but rather those variables thought to be most essential and the diagnostic techniques which are presently thought to be most reliable.

For the ac/dc electric field measurements, four antennas are required to determine the vector $\vec{E}$. By using spherical sensors at the ends to maximize the effective length, accurate dc field measurements can be made with antennas of approximately 15-meter maximum extension. By mounting a second set of spherical sensors about 1.5 meters from the ends, the same antenna can observe short wavelength electrostatic oscillations from 10^{-2} Hz to 100 kHz. The onboard instrumentation for these measurements should include spectral analyzers and visual display of the spectrum, in addition to normal data recording, to allow detection of plasma waves in the ambient medium and to allow monitoring of waves and electric fields associated with active experiments. For accurate ac/dc electric field measurements, the spacecraft velocity must be known to within a few meters per second, the antenna must not be located on B-field lines that are common with the Shuttle, and its orientation with respect to the ambient B-field and the inertial coordinates should be known to within 0.05 deg. This would permit measurement of the electric field to an accuracy of 0.1 mV/m.

The retarding potential analyzer (RPA) can determine the total ion concentration to within a few percent and can also be designed so that plasma drifts parallel to the probe face can be determined to an accuracy of about

TABLE 2. REQUIRED AMBIENT MEASUREMENTS AND INSTRUMENTS

Variables	Instrument	Weight on Boom Platform kg (lb)	Shuttle Support Required
Vector dc Electric Field	Three long, fully retractable dipoles formed from four 15-meter antennas with spherical sensors on the end	8.2 (18)	Attitude control to 1.0 deg; attitude determination to 0.05 deg; trajectory information to 10 m/sec with onboard computer to subtract $\vec{V} \times \vec{B}$
Vector ac Electric Field (Long Wave-length, 10^{-2} Hz to 100 kHz)	Same as above	Included above + 0.45 (1)	Spectrum analyzers and film or digital storage of spectral data; computer or analog x-correlation techniques combined with magnetic field measurements to determine Poynting vector; limited analog recording capability
Vector ac Electric Field (Short Wave-length, 10^{-2} Hz to 100 kHz)	Same as above, except that a second sphere 0.3 to 1 meter from the end of the long antenna is used as the second electrode	Included above + 0.45 (1)	Included above
Vector dc and Low Frequency Magnetic Field (10^{-2} Hz to 10 Hz)	Triaxial fluxgate on short boom	2.3 (5)	Included above
Ion Flow Velocity	Ion trap (directional)	0.45 (1)	Included Above
Ac Magnetic Field (10 Hz to 100 kHz)	Two or three axis magnetic loop detectors	1.4 (3)	Included Above
Plasma Density and Electron Temperature	Cylindrical Langmuir probe on short boom; rf probe	1.4 (3)	(*) Altitude control to 10 deg, determined to 1 deg
Fluctuations in Plasma Density (Electrostatic Waves)	Spherical and cylindrical probes on short booms	Included above + 0.45 (1)	Included in (*)
Ion Temperature and Composition	Retarding potential analyzer Ac Langmuir probe Rf mass spectrometer	1.4 (3) 1.4 (3) ≈ 2.3 (5)	Included in (*)
Super Thermal Ions and Electrons (0 to 500 eV)	Retarding potential analyzer; hemispherical electrostatic analyzer	Included above ≈ 2.3 (5)	Included in (*) and active control of platform potential
Energetic Fluxes of Protons and Electrons (0.5 to 20 keV)	Electrostatic analyzers	≈ 2.3 (5)	Included in (*)

1 m/sec. (Drifts up to 500 m/sec may occur along B-field lines and would not be observed by E-field measurements.) The RPA is directional and must be oriented to within 10 to 15 deg of the velocity vector of the spacecraft and known to within 1 deg.

Langmuir probes of planar, cylindrical, and spherical geometries have been used effectively to determine electron temperatures, the number density of thermal electrons, and the space potential. There are two distinct techniques in use, the standard Langmuir analysis which uses the current-voltage characteristic of the probe and the methods which use the first and second derivatives of the current-voltage curve. The standard analysis has considerably higher sensitivity and can, therefore, be used in lower density plasmas, while the derivative method can be used to reduce the effects of photoelectrons. Generally this method uses ac techniques to obtain the derivatives and, because the ac signal is very small, this limits the sensitivity of the instrument to densities on the order of 300 electrons/cm^3. However, this is probably adequate for wake measurements at the altitudes of the Shuttle orbits.

Such a CORE diagnostic package should be flexible, allowing for expansion and/or modification as new information and improved experimental techniques dictate. Because of the size of the Shuttle, it is essential that the CORE package be mounted on a boom which is of sufficient length and oriented in such a way that it provides contact of the diagnostic instruments with the undisturbed medium.

2. WAKE AND SHEATH MEASUREMENTS

The currently available diagnostic instruments and techniques appear to be adequate for the initial wake and sheath studies. A suitable complement of instruments would essentially consist of those suggested in Table 2 for the CORE instrument package. However, certain modifications to the probe heads and antennas will be required to meet requirements peculiar to the wake and sheath zones.

The antenna array for ac/dc electric field measurements should be similar to the CORE instrument, but the antennas should be shorter (approximately 1.5 meters) and fully retractable to prevent interference with mapping maneuvers and other measurements. The low plasma density in certain regions of the wake may complicate electric field measurements somewhat. However, such an array should provide sufficient accuracy for dc electric field measurements in most of the wake region, since larger fields are expected, and will provide a high sensitivity to any short wavelength electrostatic waves that may be present.

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The wake region has been almost entirely avoided heretofore by experimenters carrying out geophysical studies. As a result, there is limited information on the behavior of the instruments in regions where the medium is not necessarily macroscopically neutral and the charged particle velocity distributions may not be Maxwellian. Such behavior would make interpretation of data from Langmuir probes and retarding potential analyzers difficult, since the standard analysis for both types of probes assumes a Maxwellian velocity distribution. It is, however, possible to use the second derivative, obtained by ac or other techniques, to measure the velocity distribution directly by the use of Druyvesteyn relations [15].

The ideal data for a proper comparison with the theory would consist of the distribution functions for charged particle velocities and the electric potential in space around the wake-generating body. However, this is not feasible for ions with the currently available diagnostic instrumentation since most RPAs and ion traps are only slightly directional (approximately 70 deg field of view) and Langmuir probes are even less so. A second, and probably sufficient, possibility is to use charged particle number density distributions in space along with the electric potential distribution. However, probes measure charged particle flux and not density. The determination of density from such measurements requires that the direction and magnitude of the mean velocity be known. It would, therefore, be desirable to have a highly directional RPA or ion trap (in addition to standard instruments) among the complement of instruments for mapping the wake. This would permit determination of the direction of the ion flux, which could be combined at a given point in space with the magnitude of the mean ion velocity (determined by standard RPA techniques) to obtain the ion number density.

The mounting requirements for diagnostic instruments were discussed previously. It should be noted, however, that the relaxation of accuracy on electric field measurements permits a corresponding relaxation on the pointing requirements of the instrument platform. Pointing requirements for standard plasma probes are less critical.

3. DIAGNOSTIC EXPERIMENTS/DEVELOPMENT

Several diagnostic methods have been proposed (ranging from proven to conceptual) for plasma wake and sheath studies in Reference 1. It is in the interest of wake and sheath studies, as well as other areas of investigation presented in Reference 1, to include as many of the different proposed diagnostic methods as is practical in the PPEPL experiments. This would provide for a comparison of instruments as well as the capability to investigate, as an

experimental program, diagnostic methods not previously used for in-situ wake and sheath studies; i.e., electron beam techniques, plasma wave techniques, Thompson scattering of electromagnetic radiation from free electrons utilizing a bistatic system and cross beam correlation techniques, etc.

The Shuttle-PPEPL facility which can provide a large degree of experimental control and onboard, real-time reduction and observation of key constituents of the data offers a unique facility for diagnostic studies. The requirements of such studies on the Shuttle and the PPEPL should not be significantly different from those already discussed for the CORE instrument package for ambient measurements.

C. Problems Requiring Further Study

1. BOOM OSCILLATION AND END TILT

At present, an insufficient amount of data is available to properly assess the dynamic characteristics of a 50-meter boom of the type proposed in Reference 2. The effects of accelerations to be encountered in typical mapping maneuvers should be evaluated and the utility of alternate mapping techniques, such as the one discussed above, should be assessed.

2. BOOM POSITIONING (SENSING/CONTROL)

It is doubtful that the 0.2 deg accuracy, to which the orientation of the base of the boom can be determined, will be sufficient for mapping smaller bodies; e.g., of about 1-meter radius. A more direct and reliable positioning technique is needed (especially in light of anticipated boom dynamics indicated above), one which would employ a ranging device to measure tip separation between the two booms directly. Accuracy of ±1 percent of the separation distance would be desirable in each dimension for small bodies (approximately 1-meter radius).

3. $\vec{V} \times \vec{B}$ VOLTAGE ON BOOM

The $\vec{V} \times \vec{B}$ potentials created on an orbiting 50-meter boom can be on the order of 20 volts. To avoid the possibility of these potentials being applied to the instrument platform or the wake generating body, or of creating a voltage between the end of the boom and the instrument platform, it is suggested that:

1. Where no current must be drawn from the plasma, booms can be insulated from their mount.

2. The booms should be either constructed of dielectric materials or coated with an insulator and actively controlled to match the potential at the end of the boom to the ambient space potential of the plasma in that location.

3. Conductors on the booms should be minimized by telemetering data to the PPEPL. If the data rates are too high, a triaxial cable can be used with the first (inside) shield acting as an ac ground between the Shuttle and the platform payload and the outer shield driven at the same dc potential as the platform, i.e., a dc ground to the platform. The outer shield should be covered with an insulator.

4. The potential of the instrument platform should be actively controlled to match the ambient space potential or floating potential. This will require either an electron gun or the use of the Shuttle body to collect current.

5. Conductors required for power transmission should be guarded as discussed in item 3 or with short sections of conducting ferrometallic shielding covered with an insulator. Power should be transmitted in the ac mode with proper filtering to isolate instruments from the Shuttle floating potential and noise.

A possible alternate method is to use batteries which would require connection to the Shuttle-PPEPL only during recharging. However, in view of the mass of the required diagnostic instruments (Table 2) and the limitations on the boom payload [25 kg (55 lb)], the use of storage batteries does not appear desirable.

4. ATMOSPHERIC EXPLORER SUBSATELLITE

To increase its utility for wake and sheath studies, the following two modifications of the basic AE Satellite are desirable and should be studied to determine their feasibility:

1. Substitution of larger control thruster to produce higher thrust for greater maneuverability.

2. Partial enclosure of the satellite in a conducting shell and operation on battery power for short-term wake and sheath experiments.

5. DIAGNOSTIC DEVICES AND TECHNIQUES

The probes and antenna discussed in the previous sections were viewed primarily as diagnostic instrumentation and not as experiments. However, as indicated in the previous discussions, the current diagnostics are not optimal and experiments to improve present techniques and develop new methods are needed. In particular, the problems resulting from secondary electrons emitted from the spacecraft surface, as well as those associated with measurements in nonequilibrium regions of the wake, should be investigated. Also, the present techniques should be compared.

IV. CONCLUSIONS AND RECOMMENDATIONS

The ability to independently maneuver a wake-generating body and a separate package of diagnostic instruments, allowed by the two 50-meter booms on the PPEPL, will provide a unique experimental capability which is sufficient to facilitate systematic investigations of the disturbed zone of test bodies in the ionospheric plasma. In view of the scientific importance of this subject, the existence of numerous and sometimes conflicting theoretical calculations, the fragmentary nature of present understanding, and the potential impact of wake and sheath effects on other experiments, it is recommended that such studies be included on the early PPEPL missions.

The working group recommends that the following major points be considered for experiments on the early PPEPL missions, with additional study and SRT efforts where necessary:

1. Investigation of boom technology with respect to:

a. The dynamic characteristics of 50-meter booms when undergoing maneuvers typically required in wake and sheath studies.

b. Alternate maneuvering techniques which allow for a complete mapping of the disturbed zone while reducing the acceleration on the booms.

c. Ways of eliminating or reducing $\vec{V} \times \vec{B}$ effects on booms and boom-mounted experiments.

2. Development of a ranging technique to accurately determine the relative X, Y, Z coordinates between the wake-generating body and the diagnostic package for separation distances of up to 100 meters.

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3. Supplementary theoretical and laboratory studies to:

a. Investigate the effects of unequal charge density and non-Maxwellian velocity distributions, which may occur in some regions of the disturbed zone, on present diagnostic techniques.

b. Continue improvement of existing diagnostic probes and analysis techniques and the development of new instruments and techniques.

c. Obtain a preliminary insight into the wake and sheath phenomena to aid in the development of experiments and experimental techniques for the PPEPL.

4. Investigation of the experimental advantages of an EVA capability compared to disadvantages, such as increased cost of the PPEPL.

5. Adaptation of a boom-mounted diagnostic package to be included in the CORE PPEPL instrumentation for the purpose of independent measurements of the ambient ionospheric plasma environment. Although only the measurement of plasma parameters are discussed in this report, in as far as possible, all aspects of the Shuttle-PPEPL environment should be determined by the CORE instrumentation.

The capabilities of the Shuttle-PPEPL facility will be greatly enhanced, especially for wake and sheath experiments, by the addition of a maneuverable subsatellite. It is recommended that the feasibility of the early addition of an Atmospheric Explorer Satellite, which can meet many subsatellite requirements, be investigated. Such a study should include an investigation of the possibility of modifying the control thrusters to obtain additional maneuverability, and battery operation on short experiments, so that an outer shell could be added to reduce the complexity of the satellite as a wake-generating body.
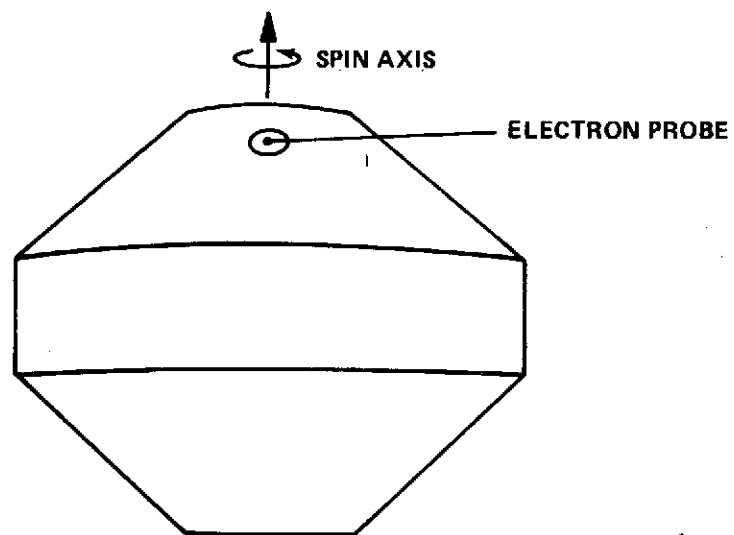
APPENDIX A — PRESENT STATUS OF IN-SITU WAKE AND SHEATH MEASUREMENTS

In contrast to laboratory experiments, in-situ experiments provide a unique capability in that measurements are taken in the natural, unbounded ionospheric plasma. Therefore, the difficulties of having to neglect some aspects of the problem, make simplifying assumptions or approximations, or resort to scaling techniques simply do not exist. In such experiments, the wake and sheath characteristics will result from the composite effects of the total spacecraft environment. To ascertain the effects of various plasma parameters, the characteristic of the ambient ionospheric plasma can be selected over the range given in Table 1 by changing the orbital altitude and/or latitude.
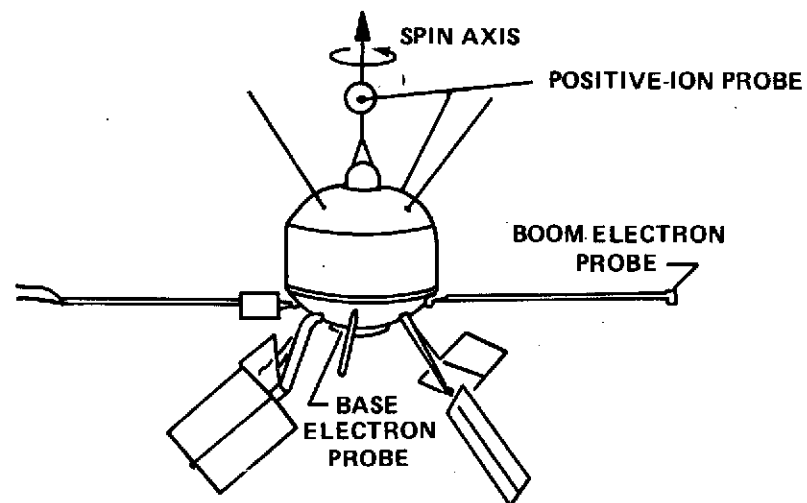
In previous in-situ experiments, it has not been possible to make full use of the inherent potential of the ionosphere as a laboratory for wake and sheath studies. With the exception of the Gemini-Agena 10 experiment, which yielded limited results, all of the available data were obtained from single-body satellites and sounding rockets. Measurements were made either from the surface of the vehicle or from short booms, which limited the acquisition of reliable data to the region immediately surrounding the wake-generating body (i.e., at distances of $1 R_0$, $2 R_0$, and $5 R_0$ from the center of the body, where R_0 is the body radius). It should also be noted that these measurements, which are not intended for use in wake and sheath investigations, were obtained with a number of different diagnostic devices and analysis techniques and involved a number of spacecraft of varied geometric and surface characteristics.

Despite the obvious limitations of the early flight measurements for the purpose of wake and sheath studies, several satellites (e.g., Explorer VIII, Ariel I, and Explorer XXXI) have produced some very useful results. The geometry of these satellites and the location of the diagnostic probes are given in Figure A-1.
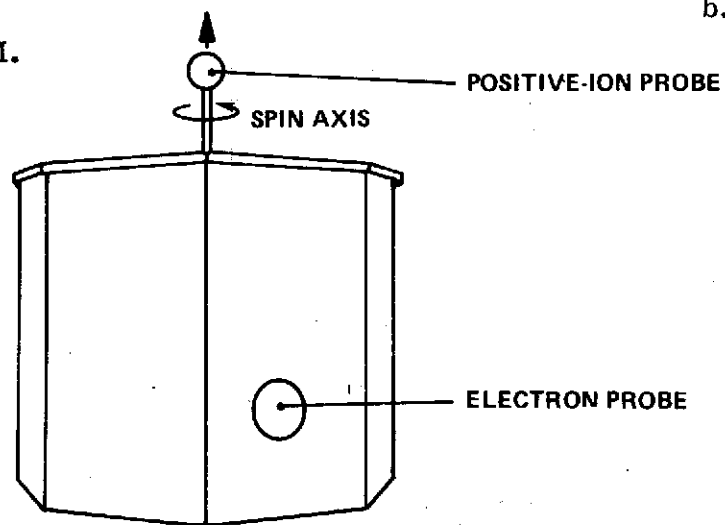
A comparison of electron current collected by the boom probe on the spinning Ariel I satellite with that collected by the base probe showed that no appreciable enhancement of electrons occurs ahead of the satellite, but a strong depletion of electrons was observed in the wake (at $1 R_0$ from the center of the satellite). The electron current in the wake was about 1 percent of ambient at an altitude of 400 to 700 km where the average ionic mass $(m_+)_{AV}$

SPIN AXIS

ELECTRON PROBE

a. Explorer VIII.

SPIN AXIS

POSITIVE-ION PROBE

BOOM ELECTRON PROBE

BASE ELECTRON PROBE

b. Ariel I.

POSITIVE-ION PROBE

SPIN AXIS

ELECTRON PROBE

c. Explorer XXXI.

Figure A-1. Geometries of the Explorer VIII, Ariel I, and Explorer XXXI satellites.

was 16. Data obtained from Explorer XXXI, where altitude was varied over a much wider range, confirmed this result, showing $|I_e(wake)/I_e(front)| = 0.01$ for altitudes where $(m_+)_{AV} = 16$. However, through simultaneous measurements of $(m_+)_{AV}$ the electron current density in the wake was observed to increase with decreasing ionic mass, which indicates a dependence on the ion velocity (or Mach) number. At altitudes where $(m_+)_{AV} = 4$, it was found that $|I_e(wake)/I_e(front)| = 0.3$, which agrees with data obtained at similar altitudes with the Explorer VIII satellite. Similarly, the electron current density of 1 percent of ambient observed at lower altitudes for $(m_+)_{AV} = 16$ agrees with measurements from the Gemini-Agena 10 experiment.

A comparison of the Ariel I and Explorer XXXI data, obtained from boom-mounted probes, yields the additional result that at a distance of 2 R_0 from the center of the satellites, $N_e \approx N_+$. This suggests that a significant part of the charged particle depletion in the wake of a body exists within approximately one radius from the surface. This result must be qualified, however, since the data for ions was obtained from a spherical ion probe on the Ariel I satellite, while the electron data were obtained from a cylindrical Langmuir probe on the Explorer XXXI satellite.

Measurements of electron current density taken with the boom probe sweeping behind the spherical ion trap on Ariel I gave an indication of current enhancement within the wake 5 R_0 downstream from the center of the body. However, no obvious enhancement was indicated by the axial ion and electron current density profiles obtained in the wake of the Gemini 10 spacecraft.

Measurements of electron current density in the wakes of both the Ariel I satellite and its spherical ion trap indicate the wake to be greater in width than the geometric wake of the body.

Analysis of the data from the boom-mounted electron probes on Explorer XXXI has indicated an enhancement of electron temperature (T_e) in the near wake by as much as 50 percent above that in the ambient plasma [10]. Also, analysis of data from Ariel I and a Black Knight rocket has given evidence for the existence of a time-variant turbulence, which exhibits strong oscillations, near the edge of the wake region [11].

In summary, in combining all the results of the available in-situ data, one obtains an indication of the following characteristics of the plasma wake behind an orbiting spacecraft:

1. The width of the plasma wake is greater than the width of the geometric wake of the body, indicating a divergence or flare of the wake.

2. At a distance of approximately 1 R_0 downstream from the spacecraft surface, the plasma has regained neutrality; i.e., $N_+ \approx N_e$.

3. At a distance of 4 R_0 downstream from the spacecraft surface, an enhancement of electron current density may occur in the center of the wake. (Although no measurements are available, this also indicates an enhancement of ion current density since $N_e \approx N_+$.)

4. A depletion of electron current density, which depends on the average ionic mass, occurs in the near wake (at the spacecraft surface). This indicates a dependence on the ion velocity (or Mach) number.

5. An enhancement of electron temperature may occur in the near wake (at the surface of the spacecraft).

6. Time-variant oscillations or turbulence may occur near the edge of the near wake.

A more detailed discussion and evaluation of these data and results is given in the review paper by Samir [4].

APPENDIX B — SUPPLEMENTARY STUDIES

Although it is anticipated that the PPEPL-Shuttle facility will provide the opportunity for more comprehensive and systematic wake and sheath studies and will eliminate the problems previously associated with satellite and sounding rocket measurements, additional theoretical and ground-based laboratory studies are needed to insure the maximum return from the new generation of in-situ experiments. Ground-based studies are needed for the development of diagnostic instruments and analysis techniques suitable for in-situ measurements in the wake region. Additional theoretical and laboratory studies are also needed to obtain common solutions to allow comparison of the various theories and comparisons of the theories with experiments (both in-situ and laboratory). Such comparisons are needed to develop experiments for the PPEPL and to properly interpret the data obtained.

A. Theoretical Studies*

The problem of theoretically calculating the structure of the wake and sheath about a satellite moving through the ionosphere is equivalent to finding a self-consistent, simultaneous solution of the Vlasov equations (collisionless Boltzmann equations) for the ions and electrons and the Poisson equation which provides the connection between the ion and electron densities and the electrical potential distribution. The plasma parameters entering the calculation are essentially those shown in Table B-1.

The difficulty in obtaining solutions to this problem is essentially a numerical one in that one needs to obtain a self-consistent, simultaneous solution to three nonlinear partial differential equations under real conditions. The equations are extremely complex and, in all of the calculations that have been attempted, a number of simplifying assumptions have been used. The satellite is usually taken to be either a sphere or cylinder, which simplifies the geometry of the problem. The surface of the satellite is usually assumed to be a conductor with surface characteristics such that the body is equipotential; secondary effects such as photoemission and secondary emission may be disregarded, and incident charged particles are assumed to be neutralized.

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* The contents of this section were taken primarily from a review paper given by L. W. Parker at the Annual Spring Meeting of the American Geophysical Union, Washington, D.C., 1973.

TABLE B-1. PARAMETERS ADOPTED IN WAKE AND SHEATH
CALCULATIONS

Source	Mach Number	Debye Number	Body Potential
Fournier [16]	1, 6, 10	1/10, 2/3	+3, 0, -1, -2.75, -6, -40
Davis and Harris [19]	6 → 7	1/25, 1/10	-20 → -1000
Call [20]	1 → 8	1/25 → 5	-0 → -40
McDonald and Smetana [21]	0 → 3	1, 3 1/3, 10	-10, -25
Maslennikov and Sigov [23]	2, 7	1, 12	-0 → -40
Liu and Jew [24, 25]	4, 8	1/20, 1/5, 1	-1, -5
Kiel et al. [26]	5, 8	1/1000, 1/100, 1/10	-3
Taylor [7]	6	2/3	-0.25 → -20
Liu and Hung [9]	4, 8	≪ 1	
Parker [22]	0, 3	∞	0, -10
Gurevich, et al. [27]	1.5 → 6, ∞	1/50, 1/10, 2/3	$(e\phi/T_e)$ = -0.25 → -3.8, -14, -35
Liu [24]	8	0 → 1/10, 1/20	$(e\phi/kT_e)$ = -25 → +25
Wu and Dryer [28]	9.85		Nonuniform

Only one species of ion is assumed to be present, although this assumption is not essential since it merely shortens the computation time. In most of the theoretical treatments, the effect of the earth's magnetic field has been neglected, and all theoretical treatments have assumed steady-state conditions. It may be that there is no true steady state; fluctuations and the generation of plasma waves by instabilities may be important in determining the wake and sheath structure. Calculations of the wake and sheath properties for such a case would be much more difficult.

The Vlasov equations for the ions and electrons are a mathematical representation of the fact that the velocity distribution of the particles is an invariant along a particle trajectory. Hence, the problem of solving the equations involves a numerical representation of the position coordinates of particles

in terms of a spatial grid, together with a method for determining the particle trajectories. A solution for the governing equations would result in values for the ion and electron velocity distribution functions and the electric potential as a function of position about the satellite. From the distribution functions, one can compute moments such as the ion and electron number densities and also current densities at desired locations, such as at the satellite surface. Some of the theoretical treatments make approximations such that only the density moments and not the particle distribution functions are obtained. These approximate treatments would be very valuable if one had a good estimate of the errors involved. Unfortunately, few exact solutions are available so this kind of evaluation has not yet been attempted.

It is convenient to classify the various theoretical treatments on the basis of how they treat the trajectory part of the Vlasov equation. Inside-out methods follow the trajectories backward in time from the point in space at which one desires to know the velocity distribution to the point of origin of the particles in the undisturbed plasma. Outside-in methods follow the trajectories forward in the same direction as the actual motion of the particles. "Other" methods are defined here to be methods which involve approximations such that trajectories are not followed.

The inside-out method has been used by Fournier to calculate the wake of a moving cylinder [16]. (Table B-1 shows the physical parameters used in the different calculations.) It was used by Taylor for a rectangular-cylinder wake to first-order only; i.e., the calculation was not carried beyond the first iteration [7]. Parker and Whipple have used the method for two-electrode probes on a satellite but have not used it yet in any wake calculations [17, 18]. Liu and Hung have used this method to develop a treatment for the far-wake zone, which predicts a wave-like behavior in this region [8, 9]. The advantages of the inside-out method are that it is flexible and points in space at which one desires to evaluate the density may be chosen at random. Also, the method is suitable for electrons as well as for ions, and solutions may be obtained, in principle, to any degree of accuracy. The disadvantage of this method is that information carried by trajectories is lost upon moving to another point in space, so that the calculation is time consuming.

The outside-in methods may be categorized into two classes, those involving flux tubes defined by two neighboring trajectories and those involving super-particles (sometimes called the method of weighted deposition). In the former class, the flux of particles in a tube is constant. Since the cross-sectional area of the tube is known from the trajectory calculation and the particle velocity is also known, the particle density may be determined at any point in the tube. This technique has been used by Davis and Harris to calculate

the wake behind a sphere in a cold ion beam [19]. The method was used by Call [20] for the wakes of a plate, disk, cylinder, and sphere in a cold ion beam, and by McDonald and Smetana [21] for the wake of a cylinder in a mono-energetic plasma with a drift. The advantage of this method is that it is a relatively fast calculation. However, the solution by this method is invalidated if trajectories cross, which is not an unrealistic condition.

The second class of outside-in methods weights the contribution of a trajectory to the density in a cell by the amount of time spent in the cell. This method was used by Parker [22] and by Maslennikov and Sigov [23] for the wake of a sphere in a cold ion beam. It has the advantage that there is no difficulty with trajectory crossings. Also, it is similar to computer simulation techniques and can be easily adapted to a simulation calculation. The main disadvantage is that many trajectories are needed to obtain good statistics within cells.

"Other" methods defined as approximate treatments avoiding trajectory calculations include the following: Liu and Jew assumed that the electron density was given by the Boltzmann factor and that the ion axial component of velocity was a constant. They were then able to evaluate the ion density analytically by assuming an additional approximate constant of the ion motion [24, 25]. Kiel, Gey, and Gustafson assumed that the ion trajectories were straight lines; that is, they were unaffected by electric fields. It was assumed that the electron densities were given by approximate formulas which were especially designed to include the effect of the potential barrier in the wake [26]. Gurevich et al. assumed quasineutrality, with both densities being given by the Boltzmann factor [27]. They also assumed that the axial component of velocity was constant for large Mach numbers. Similar methods were used by Wu and Dryer to compute proton density and velocity contours for the interaction of the solar wind with planetary bodies [28].

There has been no systematic comparison of the results of these various calculations with each other, probably as a result of the small number of cases for which solutions are available. It would be especially useful to compare the approximate treatments with a more exact calculation so that one would know where the approximate calculations could be employed. The approximate treatments would be useful also as initial solutions for the iteration procedure necessary for the more exact treatments.

To obtain an experimental corroboration of a theoretical calculation, it would be ideal to have the particle velocity distributions and the electric potential as functions of position about the satellite. This requirement may not be

realistic, however, in which case experimental values for the ion and electron densities and the electric potential as functions of position about the body would have to suffice. Useful comparisons have been made by Samir and Jew with less data; namely, the ion and electron current densities measured at the satellite surface as a function of angular position [29]. Similar comparisons of theory with experimentally determined electron and ion current densities were made by Gurevich et al. [27].

While theoretical treatments currently suffer from the necessity of making simplifying assumptions and approximations (which cannot always be justified) in order to obtain solutions, further development in this area, to the point where reliable theory-theory and theory-experiment comparisons can be made, would do much to enhance the understanding of the governing mechanisms of the wake and sheath phenomena and to effect a proper interpretation of future in-situ data.

B. GROUND-BASED LABORATORY STUDIES

Laboratory plasma physics experiments which have potential application to the development of experiments for the PPEPL lie primarily in two areas of investigation: (1) those involving the improvement of existing (or the development of new) diagnostic devices and techniques and (2) those involving the study of collisionless plasma flow over various types of bodies, which can be scaled in an attempt to obtain properties similar to those in space. The laboratory wake and sheath experiments can also be carried out for conditions other than those encountered in space (particularly those within the range of the Space Shuttle) which are of interest for comparison with the more general theories.

1. DEVELOPMENT OF DIAGNOSTIC TECHNIQUES

Laboratory plasma research facilities are capable of providing controlled and well-known plasma conditions which are suitable for the development of diagnostic devices and comparison of such devices with existing techniques. The new devices and techniques developed under such a program would be essentially proven and understood when required for in-situ investigations. Also, some diagnostic techniques presently used in labroatory facilities could significantly enhance in-situ studies if developed for use as flight hardware, particularly electron beam techniques which have been used successfully in laboratory studies to determine the electric fields associated with antennas for topside and sounding measurements.

Laboratory studies were also useful in investigating the discrepancies between the values of ion temperature obtained from RPA measurements on the OGO-3 and OGO-4 satellites and ground-based radar backscatter techniques. These studies showed that a significant part of the discrepancy resulted from potential sag between the grid wires of the RPA and they provided a technique for effectively eliminating most of this error [30].

Further investigation in this area is needed to deal with diagnostic problems which are directly associated with the diagnostic requirements of the PPEPL. Examples of these which are peculiar to wake and sheath studies include: (1) the need to determine charged particle density as a function of position in the wake (which implies an accurate determination of the magnitude and direction of the mean particle velocity, as well as the magnitude of the particle flux at each point), (2) the behavior of various diagnostic devices within the wake region, and (3) the effectiveness of the various techniques for analysis of data obtained in this region.

2. LABORATORY WAKE AND SHEATH STUDIES

Laboratory studies, so far, have provided primarily a rather qualitative, overall view of the distribution and behavior of ions in the near-to-midwake regions [6, 31-36]. There has also been some investigation of ion behavior in the mid-to-far-wake regions [5]. However, very little effort has been directed toward studies of the distribution and behavior of electrons in the disturbed zone for ionospheric-type plasmas.

The above studies have indicated several basic characteristics of the wake and sheath regions under laboratory conditions. Some examples of these are:

1. An essentially total void of ions in the near-wake region.

2. Filling of the void region in item 1 in such a manner as to form an enhancement of ion flux in the midwake region.

3. The ion flux enhancement of item 2 peaks at a distance downstream given approximately by $S \cdot R_0$ (the product of the ion velocity, or Mach number, and the body radius) for electrically floating bodies.

4. The peak ion flux enhancement has an amplitude which may range from something less than ambient to several times the ambient flux density, depending on the plasma parameters.

5. The ion flux peak has been observed to divide and form a wavelike structure in the far-wake region.

6. Parameters such as S (the ion Mach number), ϕ_N (the normalized body potential), and R_0/λ_D (the inverse of the Debye ratio) have been observed to affect length and structure of the wake zones.

Although theoretical calculations are available for relatively few cases, several comparisons, of a very qualitative nature, of experimental results with various theories have been made [2, 3, 27, 28]. These comparisons indicate that while the neutral approximation seems to provide a relatively accurate description of the far wake, electric fields must be considered in treatments of the near and midwake regions.

Unfortunately, many of these studies were carried out for conditions which are unsuitable for comparison with ionospheric measurements. At best, only a partial simulation of the ionospheric conditions was achieved, neglecting such factors as the geomagnetic field, thermal motion of ions, and the multiple ion components characteristic of the ionospheric plasma (most studies used relatively massive Argon plasmas).

Additional investigations are needed in this area to provide a foundation for the development of experiments and experimental techniques for the PPEPL and to aid in the interpretation of the in-situ data. Such studies should be more closely aligned with what is known from the currently available in-situ data and theoretical solutions. They should also include investigations of electron behavior, as well as that of ions, taking into account, as far as possible, the above omissions of previous investigations.

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APPROVAL

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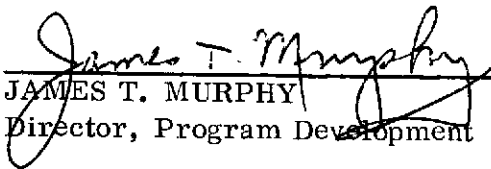
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This document has also been reviewed and approved for technical accuracy.

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